CHARACTERISTICS OF COAL ASH MIXTURES AS REPLACEMENT MATERIALS IN GROUND IMPROVEMENT WORKS

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To my respectful parents, beloved wife Noraishah Hj. Abdul Rahman
and my children; four Amirul (sons), Ahmad Amirul Asyraf,
Ahmad Amirul Aiman, Ahmad Amirul Afif and Ahmad Amirul Waidz
and three daughters, Ainatul Mahirah, Aina Balthisya and Afrina Raisya Balqis

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ABSTRACT

Fly ash (FA) and bottom ash (BA) are two of the coal ashes by-products produced from coal-fired power plants. They are usually disposed off together as a waste in utility disposal sites with a typical disposal rate of 80% FA and 20% BA. The use of coal ash in construction projects that require large volume materials, such as in soil improvement works, is highly promising in solving the disposal problem. The aim of this research is to determine the suitability of FA-BA mixtures as replacement materials for soft soil foundation. Representative samples of coal ash were collected from Tanjung Bin Power Plant, Pontian, Johor. Six mixtures of FA and BA with different mix ratios of 0%, 30%, 50%, 70%, 90% and 100% FA content by weight had been used in this study. The coal ash mixtures were compacted at 95% of maximum dry density, sealed and cured for 0, 14, and 28 days before being analysed for material characterization, mechanical properties and chemical analysis. The performance of FA-BA mixtures as replacement materials had been determined through laboratory physical model tests. In model test, 40 cm height (H) of soft kaolin clay (about 20 kPa undrained strength) was replaced fully and partially by FA-BA mixtures (H_m) at replacement ratio, H_m/H = 0, 0.125, 0.375 and 1.0. In general, the results of the laboratory tests indicate good performance of FA-BA mixtures. Morphological analysis shows that the number of irregular shaped particles increased confirming change in material type with curing period. The results also show that mixtures with higher fly ash composition have less drainage characteristics but can be improved by prolonging the curing period. The shear strength of coal ash mixtures varied depending on the FA content. The maximum shear strength was obtained at the mixture of 50%FA with the friction angle values ranged from 27^0 to 37^0 that increased with curing period. The California Bearing Ratio (CBR) values increased while compressibility decreased with curing periods due to pozzolanic reaction. CBR values and compressibility of the mixtures also generally decreased with the increased of FA content. Results suggest that ash mixtures are non-corrosive while the heavy metals concentration is below the limit set by respective authority. Since the mixture of 50%FA-50%BA has the highest strength and considerably low compressibility, it can be concluded that this mixture is the most suitable mixture for replacement of soft soil. The result of physical model tests concluded the suitability of FA-BA mixtures as full or partial replacement materials of soft clay that gives promising effect in terms of decreasing the settlement of the footing placed on top of the soil. Based on this, preliminary design charts had been developed for the usage of FA-BA mixtures in geotechnical engineering works. This could help the engineers not only in designing the depth of soil to be replaced in soil improvement works but also in other purposes that rely on the strength of the eco-friendly ash mixtures.

ABSTRAK

Abu terbang (FA) dan abu bawah (BA) adalah dua daripada keluaran sampingan yang terhasil daripada loji tenaga arang batu. Bahan ini biasanya dilupuskan bersama sebagai bahan buangan di tapak pelupusan utiliti dengan kadar pelupusan 80%FA dan 20%BA. Penggunaan abu arang batu dalam projek-projek pembinaan yang memerlukan bahan yang banyak seperti dalam kerja-kerja pembaikan tanah, adalah sangat memberangsangkan dalam menyelesaikan masalah pelupusan. Tujuan kajian ini adalah untuk menentukan kesesuaian campuran FA-BA sebagai bahan gantian untuk tanah asas yang lembut. Sampel abu arang batu telah dikumpulkan dari loji janakuasa Tanjung Bin, Pontian, Johor. Enam campuran FA dan BA dengan nisbah campuran yang berbeza; 0%, 30%, 50%, 70%, 90% dan 100% kandungan FA mengikut berat telah digunakan dalam kajian ini. Campuran abu arang batu telah dipadatkan pada 95% ketumpatan kering maksimum, dibalut dan diawet kepada tempoh masa 0, 14, dan 28 hari sebelum dianalisis untuk pencirian bahan, sifat mekanik dan analisis kimia. Prestasi campuran FA-BA sebagai bahan gantian telah ditentukan melalui ujian model fizikal makmal. Dalam ujian model, 40 cm (H) ketinggian tanah liat kaolin lembut (kira-kira 20 kPa kekuatan tak tersalir) telah digantikan sepenuhnya dan sebahagiannya oleh campuran FA-BA (H_m) pada nisbah penggantian, H_m/H = 0, 0.125, 0.375 dan 1.0. Secara umum, keputusan ujian makmal menunjukkan campuran FA-BA berprestasi baik. Analisis morfologi menunjukkan bahawa bilangan zarah berbentuk tidak teratur meningkat mengesahkan perubahan jenis bahan dengan tempoh pengawetan. Keputusan juga menunjukkan bahawa campuran dengan komposisi abu terbang yang lebih tinggi mempunyai ciri-ciri saliran yang lebih rendah tetapi boleh ditingkatkan dengan memanjangkan tempoh pengawetan. Kekuatan ricih campuran abu arang batu berubah bergantung kepada kandungan FA. Kekuatan ricih maksimum adalah pada campuran 50%FA dengan nilai sudut geseran antara 27^0-37^0 yang meningkat dengan tempoh awetan. Nilai Nisbah Menggalas California (CBR) meningkat manakala kebolehmampatan menurun dengan tempuh awetan disebabkan oleh tindak balas pozzolanik. Nilai CBR dan kebolehmampatan daripada campuran juga umumnya menurun dengan peningkatan kandungan FA. Keputusan menunjukkan bahawa campuran abu adalah tidak menghakis manakala kepekatan logam berat adalah di bawah had yang ditetapkan oleh pihak berkuasa. Disebabkan campuran 50%FA-50%BA mempunyai kekuatan tertinggi dan kebolehmampatan agak rendah, ia boleh disimpulkan bahawa campuran ini adalah campuran yang paling sesuai untuk menggantikan tanah lembut. Hasil ujian model fizikal menyimpulkan kesesuaian campuran FA-BA sebagai bahan gantian tanah liat lembut secara penuh atau sebahagian yang memberikan kesan baik dari segi mengurangkan enapan asas yang diletakkan di atas tanah. Berdasarkan ini, carta reka bentuk awal telah dibangunkan untuk penggunaan campuran FA-BA dalam kerja-kerja kejuruteraan geoteknik. Ini boleh membantu jurutera bukan sahaja untuk pemilihan kedalaman tanah yang akan digantikan dalam kerja-kerja pembaikan tanah tetapi juga untuk tujuan lain yang bergamttung kepada kekuatan campuran abu yang mesra alam.

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LIST OF ABBREVIATIONS

AAS	-	Atomic absorption spectroscopy
ACAA	-	American Coal Ash Association
ASTM	-	American Society of Testing Material
BA	-	Bottom ash
BS	-	British standard
CCP	-	Coal combustion product
CD	-	Consolidated drained
CU	-	Consolidated undrained
FA	-	Fly ash
FA-BA	-	Fly ash – bottom ash
FBA	-	Furnace bottom ash
FEA	-	Finite element analysis
FGD	-	Flue gas desulfurization
HSM	-	Hardening soil model
JKR	-	Public works department
LEM	-	Linear elastic model
MCCM	-	Modified cam clay model
MCM	-	Mohr coulomb model
OMC	-	Optimum moisture content
PFA	-	Pulverised fuel ash
SEM	-	Scanning electron microscopy
SG	-	Specific gravity
SSM	-	Soft soil model
UCS	-	Unconfined compressive strength
UK	-	United Kingdom
ULS	-	Ultimate limit state
USA	-	United States of America
USCS	-	Unified soil classification system
UTHM	-	Universiti Teknologi Tun Hussein Onn
UTM	-	Universiti Teknologi Malaysia
TGA	-	Thermal gravimetric analysis

XRD	-	X-Ray diffraction
XRF	-	X-Ray fluorescence

LIST OF SYMBOLS

B	-	Width of foundation
c	-	Cohesion of soil
C_c	-	Compression index
$c_{increment}$	-	Cohesion increment
c_{peak}	-	Peak cohesion
$c_{d\ peak}$	-	Peak cohesion for consolidated drained
c'_{peak}	-	Peak cohesion for consolidated undrained
$c_{residual}$	-	Residual cohesion
$c_{d\ residual}$	-	Residual cohesion for consolidated drained
$c'_{residual}$	-	Residual cohesion for consolidated undrained
C_s	-	Swelling index
c_u	-	Undrained shear strength
C_U	-	Coefficient of uniformity
c_v	-	Coefficient of consolidation
D	-	Depth factor
D_f	-	Depth of foundation
DH	-	Depth to firm stratum
D_{10}	-	Effective size
D_{30}	-	Diameter finer than 30 %
D_{60}	-	Diameter finer than 60 %
E	-	Young's stiffness
$E_{increment}$	-	Stiffness increment
E_m	-	Young's stiffness of aluminum alloy
E_{oed}	-	Oedometer stiffness
E_p	-	Young's stiffness of concrete
E_{ur}	-	Unloading stiffness
E_{50}	-	Secant stiffness
F	-	Factor of safety

g	-	Gravity, 9.81 m/s^2
G_0	-	Elastic shear modulus
G_{ref}	-	Shear modulus
G_s	-	Specific gravity
H	-	Height of embankment
h	-	Thickness of soil layer
H_s	-	Depth of failure
I_p	-	Plasticity index
k_x	-	Horizontal permeability
k_y	-	Vertical permeability
L_s	-	Linear shrinkage
m_v	-	Coefficient of volume change
N	-	Scale factor
N_s	-	Stability coefficient
t	-	Test time
w	-	Natural water content
w_L	-	Liquid limit
w_{opt}	-	Optimum moisture content
w_p	-	Plastic limit
β	-	Slope angle
ε_a	-	Axial strain
ϕ	-	Internal friction angle
ϕ_{peak}	-	Peak friction angle
$\phi_{d\ peak}$	-	Peak friction angle for consolidated drained
ϕ'_{peak}	-	Peak friction angle for consolidated undrained
$\phi_{residual}$	-	Residual friction angle
$\phi_{d\ residual}$	-	Residual friction angle for consolidated drained
$\phi'_{residual}$	-	Residual friction angle for consolidated undrained
γ	-	Unit weight of soil
γ_d	-	Dry unit weight of soil
γ_{dmin}	-	Minimum dry unit weight of soil
γ_{dmax}	-	Maximum dry unit weight of soil
γ_{sat}	-	Saturated unit weight of soil

γ_{unsat}	-	Unsaturated unit weight of soil
ν	-	Poisson ratio
σ_n	-	Normal stress
σ_1	-	Major principle stress
σ_3	-	Minor principle stress
τ	-	Shear stress
ψ	-	Angle of dilatancy

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CHAPTER 1

INTRODUCTION

1.1 Background of Research

Coal is largely used around the world as a source or power generation. In Peninsular Malaysia, the existing coal-fired power plants are Sultan Azlan Shah Power Station, Manjung Perak (3 x 700 MW) commissioned in 2003, Sultan Salahuddin Abdul Aziz Power Station Kapar (4 x 300 MW, 2 x 500 MW) commissioned in 1988, Tanjung Bin, Pontian, Johor (3 x 748 MW) commissioned in 2005 and Jimah Port Dickson (2 x 752 MW) commissioned in 2008, as shown in Figure 1.1. Sarawak has two coal fired-power plants which are Mukah (2 x 135 MW) and Sejingkat (2 x 50 MW, 2 x 55 MW) (Coal-Fired Power Plants in Malaysia, 2010). Looking at the electricity generation mix, the percentage of coal remains stable at an average of 8.6 percent from 1993-2010 and increased slightly to 12 and 14.1 percent in 2001 and 2002 respectively. However, in 2003, the percentage increased tremendously from 14.1 percent to 24.6 percent of coal in the electricity generation mix due to the commissioning of Sultan Azlan Shah Power Station Manjung. According to Joseph (2005), with the two more new constructed coal-fired power plants, Jimah, Port Dickson Negeri Sembilan and Tanjung Bin, Pontian Johor, coal consumption has been expected to increase from 11 million tonne to 21 million tonne in year 2012.

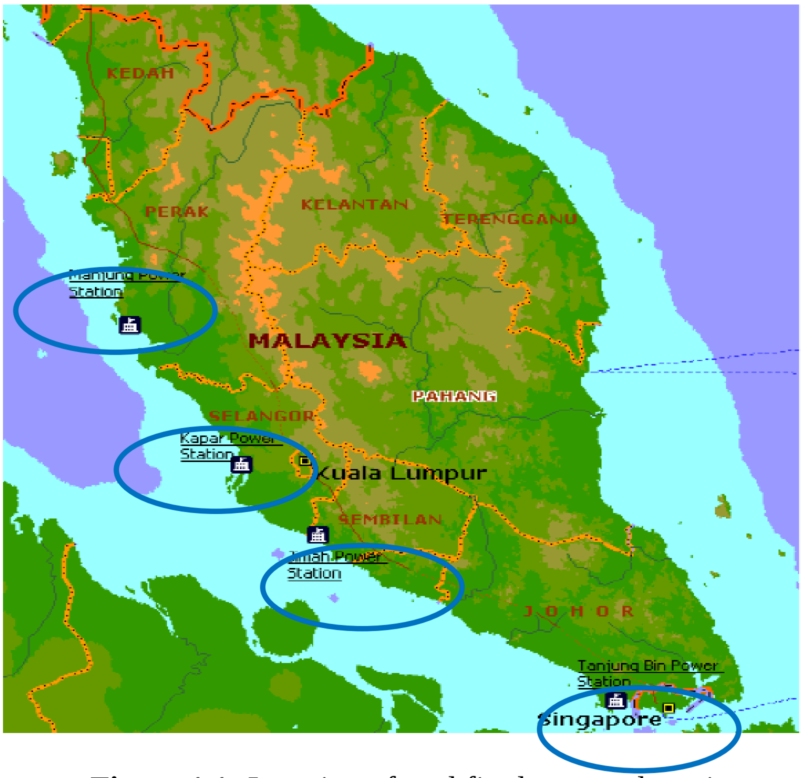

Figure 1.1: Location of coal fired power plants in Peninsular Malaysia (Mahmud, 2008)

The burning of coal for power generation produced solid waste, referred to as coal ash. The solids wastes are classified as fly ash (FA), bottom ash (BA), boiler slag and fuel gas desulfurization (FGD). The large utilization of coal produces a large volume of coal ash. In general, about 10% of the coal burned produces ash (Huang, 1990, Karim, 1997, Muhardi, 2010 and Hassan, 2013). According to the American Coal Ash Association (ACAA, 2003), the general production ratio of fly and BA is approximately 80:20. The heavier ash that drops through the bottom of the furnace, where it is collected in a funnel, is called BA. It is classified as wet or dry BA depending on the type of furnace used and it is relatively coarse grained. The lighter FA is carried through the boiler with the exhaust gases and is collected by ash precipitators (Huang, 1990). FA accounts for 70 to 80 percent of the coal ash produced by most electric power plants while BA constitutes about 10 to 18 percent of the overall ash.

According to Mahmud (2003), the coal power plants in Malaysia are usually designed using coal as blended materials in which bituminous coals are mixed with sub-bituminous coal with the proportion of 70 %: 30 %. The main reason is to reduce the cost of purchasing bituminous coal. The ash produced from this blended coal might possess different properties as compared to the ash produced from the sole use of bituminous coal or solely of sub-bituminous coal.

Basically the applications or potential applications of coal ash include the cement and concrete industries, production of synthetic aggregates and zeolites, backfill and embankment materials for highway construction, stabilization of engineered soils for construction purposes, and improvement of soils behaviour for agriculture and horticulture (Mahmud, 2008). The geotechnical, geochemical and mineralogical properties of the coal combustion products may vary from individual sample depending on the type of raw materials, feedstock handling and inflammation condition.

Several projects in the United States of America (USA) and the United Kingdom (UK) that use FA in embankment construction as structural materials have shown economic savings, both to the highway department and power plant companies (Yoon *et al*., 2009; Kim, 2003; Golden and DiGioia, 2003 and Sear, 2001). In Malaysia, however, there are still no well-known projects utilizing FA or BA as materials in any Geotechnical Engineering or construction work. This may be due to the fact that no abundant or excess of FA has been produced to date. As for BA, perhaps it is because the properties have yet to be adequately looked into.

Pandian (2004) and Muhardi (2010) reported that, FA has good potential for use in geotechnical engineering application. Its low specific gravity, freely draining nature, ease of compaction, insensitiveness to change in moisture content, good frictional properties, and others can be fully exploited in the construction of embankment, roads, reclamations of low-lying areas and fill behind retaining structures. It can also be used in reinforced concrete construction.

BA particles are much coarser than FA. The grain size typically ranges from fine sand to gravel in size. According to Kumar and Vaddhu (2003), chemical composition of BA is similar to FA but typically contains greater quantities of carbon. BA tends to be relatively more inert because the particles are larger and more fused than FA. Since these particles are highly fused, they tend to show less cementitious/pozzolanic activity and less suited as a binder constituent in cement or concrete products. However, BA can be used as a concrete aggregate or for several other civil engineering applications where sand, gravel and crushed stone are used. Chemical composition of both FA and BA shows some cementitious /pozzolanic properties, which can result in time dependent change in the properties of products made using this type of FA and BA.

A lot of studies had been concentrated on the properties of coal ash, but the investigation on the coal ash mixtures is very limited. Kumar and Vaddu (2003) observed that strength and stiffness of FA and BA mixtures vary with the curing periods. Karim (1997) examined the effect of mixture proportions of FA and BA on compaction and shear strength. He reported that the behavior of FA mixed with BA (FA-BA mixtures) varies with the mixture proportions. For usage as fill materials, it is anticipated that FA-BA mixtures will give economic advantage in which the cost of purchasing the fill material will be reduced significantly. The utilization of FA-BA mixture may answer the disposal and environmental problems in power plant industry, beside an alternative lightweight material for embankment construction on soft clay, as soil stabilization and in engineering construction. Due to lightweight properties and strength gained with time, these materials hypothetically could be used as replacement of soft soils, either in full replacement or partial replacement.

Physical models play a basic role in the development of geotechnical engineering understanding. Physical modelling is carried out to validate theoretical or empirical theories. Normally, physical modelling is performed to study the particular aspects of the behaviour of prototypes. Full scale testing is an example of physical modelling, where all features of the prototype are reproduced at full scale.

However, most physical models are constructed at smaller scales than the prototype because it is expected to obtain information of response more rapidly and allow more control over model details than full scale testing. One example of the small scale physical modelling would be the laboratory physical model. As an example, in the laboratory embankment model test, the material such as the soil to be used can be chosen easily, while the boundary and loading conditions of the model can be varied without difficulties. The costs of individual tests are correspondingly lower than the full scale tests (Muhardi, 2010).

1.2 Problem Statement

Every year, the coal-fired power plant produced large volume of coal ash which are FA and BA all over the world. Malaysia is also not excluded as a contributor of large volume of FA and BA. Even though there is no report about the producing of coal ash annually in Malaysia, but basically, about 10% of total weight of the coal burned produces ash. Both the FA and BA is disposed as waste materials. Landfill has been the primary method of disposal of these waste materials. The problems that occur to disposing this coal ash are limited availability of land and very costly since large volume of coal ash is generated. Besides that, the coal ash presents a significant environmental problem to the surrounding area. However, this environmental problem can be minimised by reducing the need for ash landfills. From these problems, many researchers have proved that FA can be used in most construction and Geotechnical Engineering works. So, many developed countries have recycled the FA and minimise all of the above mentioned problems.

The used of BA is still very insignificant compared to the FA. Besides that, the research about coal ash mixture properties is also very limited. Since FA particle are very fine, mostly spherical and vary in diameter while BA particles are much coarser than FA, the mixture of both materials will have a good potential in construction industry, in particular the Geotechnical Engineering works. Hence, a research is necessary to determine various properties of FA-BA mixtures such as a physical, mechanical, chemical, microstructure and mineralogical, especially their variation with time. This is because previous study showed that there was pozzolanic reaction in FA-BA mixture. The usage of large volume of both FA and BA as FA-BA mixture in geotechnical application may offer an attractive alternative, provided that their properties and behaviour are fully known. However, although there are a lot of studies related to the properties of coal ash internationally, the investigation about the local coal ash is very limited. In particular for FA-BA mixture, the work is insignificant, locally and internationally.

1.3 Objectives of Research

The aim of this research was to determine the suitable of FA-BA mixtures in Geotechnical Engineering work, particularly as full and partial replacement of soft soil based on laboratory experimental works and laboratory physical model tests. In order to achieve the aim of this research, the following objectives have been fulfilled:

1. To determine the compaction characteristics of various FA-BA mixtures.
2. To determine various properties of compacted FA-BA mixtures such as the physical, mechanical and chemical properties as well as the microstructure and mineralogical characteristic and their changes with time.
3. To determine the settlement performance of soft kaolin with and without the replacement of FA-BA mixtures by means of single gravity laboratory physical model tests.
4. To develop design charts for application of FA-BA mixtures as alternative materials in geotechnical engineering works.

1.4 Scope of Research

In order to achieve the objectives of this research, the following scope had been covered:

1. The coal ash used in this research had been collected from Tanjung Bin Power Plant in Pontian, Johor. Samples of bottom ash were taken from the ash pond while the fly ashes were taken from ash hoppers.
2. FA-BA mixtures had been prepared at six (6) different FA contents (0%, 30%, 50%, 70%, 90% and 100% by weight of the total samples) and tested at three (3) curing periods (0, 14, and 28 days).
3. The laboratory physical model was constructed to examine the settlement of single layer of soft clay and soft clay with fully and partially replaced by FA-BA mixtures.

1.5 Significance of Research

1. Stabilisation mechanism of FA-BA mixtures had been established and this contributed to the existing state of knowledge.
2. Properties and behavior of various FA-BA mixtures with time, established from this study would be a reference to Geotechnical Engineers in considering the usage of these materials in Geotechnical Engineering works and construction. These could also be a baseline for researchers working on FA-BA mixtures in the future.

3. The developed design charts on the usage of FA-BA mixtures in Geotechnical Engineering work, particularly as soft soil replacement could be used by other researchers as validation for numerical modeling on the performance of FA-BA mixtures as soft soil replacement.

4. FA-BA mixtures would give economic advantage in which the cost of purchasing the fill material would be reduced significantly. The environmental impact of construction utilizing coal FA-BA mixtures may be a concern to potential users of these materials. Results from this research show that FA-BA mixtures will not give detrimental effects on their surrounding environments. The utilizations of FA-BA mixtures may answer the disposal and environmental problems in power plant industry, beside an alternative lightweight material for replacement of soft subgrade soils or as backfill in embankment construction on soft soil.

1.6 Thesis Organisation

The thesis consists of eight (8) chapters. The essence of each chapter is as follows:

Chapter 1 gives the introduction of the research that includes background, statement of problem, objectives, scope and significance of research.

Chapter 2 reviews the generation of coal ash, its collection, disposal, production and utilization in the world. An overview of the physical characteristics, chemical and engineering properties of FA, BA and FA-BA are presented. Others are also discussed that include the soft clay problems and physical modelling of embankment.

Chapter 3 discusses the research methodology including the overview of the research activities, testing programme, research planning and schedule, and preparing of sample. The design, construction and testing of laboratory physical model tests are also discussed.

Chapter 4 discusses the physical and mechanical characterization FA-BA mixtures, including compaction, permeability, strength and compressibility characteristics. This chapter also addresses the effect of curing age of 0, 14 and 28 days on the properties of FA-BA mixtures and the effects of FA composition in the FA-BA mixtures.

Chapter 5 summarizes and discusses and the results of morphology, mineralogy, chemical and corrosivity characteristics of FA-BA mixtures, including SEM, XRD, XRF. This chapter also addresses the effect of FA compositions in the ash mixtures and the curing periods on the properties of FA-BA mixtures.

Chapter 6 contains the performance of settlement analysis from the experimental work by laboratory physical model tests. It includes the settlement of soft clay layer and the soft clay layer which was fully and partially replaced by FA-BA mixtures.

Chapter 7 explains the development of the design charts of coal ash mixtures as alternative materials in geotechnical engineering works based on the results of the experimental work and physical model. The conclusion and recommendations for further research as drawn from this study are described in Chapter 8.

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